Autonomy

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New Millennium Workshop

Autonomy IPDT

May 14 - 16, 1996

San Antonio, TX

G. K. Man & Gregg Swietek

Agenda

- Membership
- Focus & Scope
- Roadmap
- Key Technologies for Flight Validations
- Roadmap Gaps

1995 Membership

Co-Leaders:	
G. Man	**JPL**
G. Swietek	**ARC**
Members:	
C. Anderson	**AFPL**
E. Curtis	**OCA Applied Optics**
L. Fesq	**TRW Space & Electronics**
J. How	**Stanford University**
R. Connerton	**GSFC**
R. Simmons	**Carnegie Mellon University**
R. Twiggs	**Stanford University**
M. Yellin	**Hughes Danbury Optical Systems**
R. van Bezooijen	**Lockheed-Martin**
Cooperating Partners:	
B. Bullock	**ISX Corporation**
J. Wertz	**Microcosm, Inc.**

Autonomy Vision for Exploration

5 yrs | 10 yrs | 15 yrs

Enables affordable new exploration

Cooperating Fleet

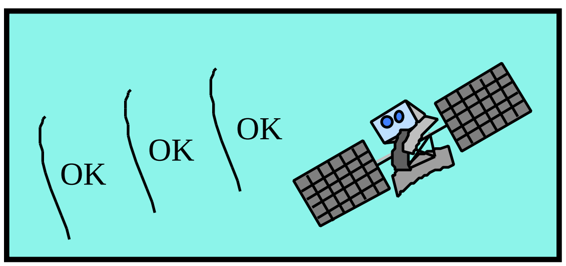
Coordinated Platforms

Self-Managing Explorer

Capability

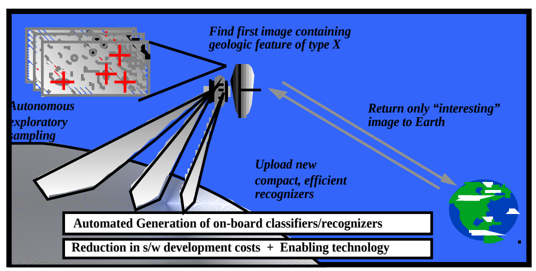
- *Handles more uncertainties*
- *Enables new science*
- *Requires fewer operations staff*

Highly Autonomous Spacecraft



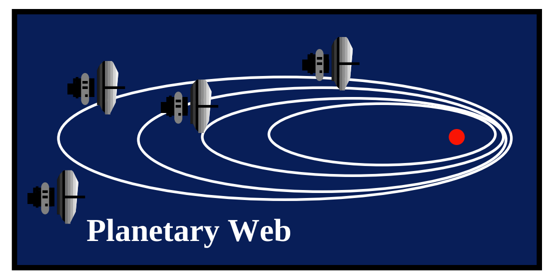
- **Self-directing spacecraft**
- **Self-protecting spacecraft**
- **Self-mobilizing spacecraft**
- **Beacon operations**

Observing & Discovery Presence Onboard



- **Trainable object recognition**
- **Knowledge discovery**
- **Close maneuvering at target**

Widespread Projection of Human Awareness



- **Multiple interacting heterogeneous spacecraft**
- **Fleet coordination**
- **Science alerts**

Autonomy - The Affordable Way to Revolutionize Exploration

Scope

Remote Agent

- Unified Flight & Ground System Software Architecture

Open Architecture: flexible, modular, “plug & play” design.

- Goal-Directed Planning, Resource Management, & Control

Autonomous mission and activities planning and scheduling; conditional sequencing

- Anomaly Detection & Fault Recovery

Automated fault detection, isolation, & recovery; known & unknown fault conditions; functional redundancy

Autonomous Guidance, Navigation & Control

- Navigation & Control

Onboard optical navigation, orbit determination & trajectory planning; autonomous station keeping; target relative maneuvering & feature tracking. Small body rendezvous & sample return.

- Sensors

Small versatile optical sensor, GPS-on-a-chip, autonomous formation flying sensor.

Science & Mission Operations

- Onboard Science Data Processing

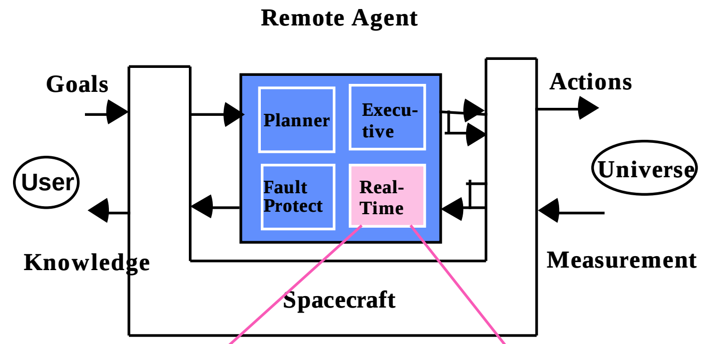
Adaptive feature recognition capabilities; “tunable” filters / recognizers; interactive & opportunistic science.

- “Justified / Beacon” Operations

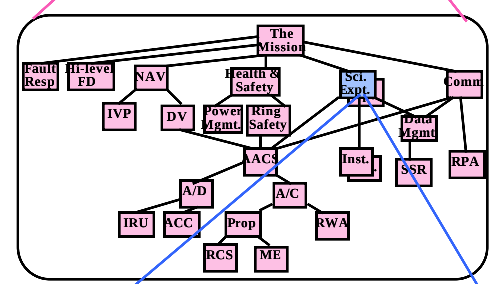
PI-directed operations; goal-directed commanding; small beacon mode infrastructure team; automated data / info dissemination.

Formation Flying

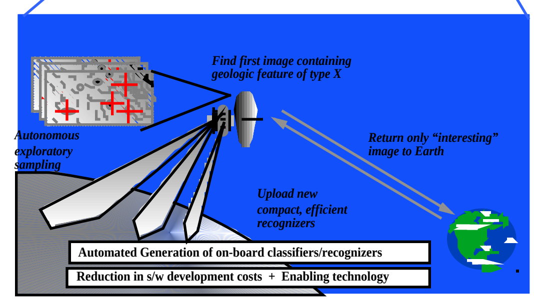
Formation keeping for multi-platform correlated observations; cluster initiation and reconfiguration; cross-platform distributed FDIR; S/C network management.



Remote Agent Superstructure



Scaleable Modular Architecture

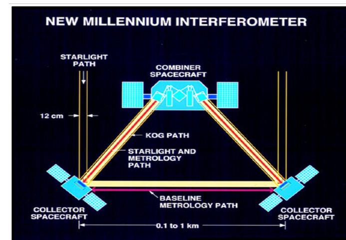


Science Data Processing

Autonomy 5-Year Roadmap

CY96 | CY97 | CY98 | CY99 | CY00

Enables affordable new exploration



Target Technology Experiment Mission → **Flyby** (Poorly-known targets asteroids & comets) → **Formation Flying** (Multi-platform missions) → **Vision**

Technology			
Planning/ Scheduling & Fault Protection	• Priority-based planning • Model-based fault diagnosis	• Replanning & time-limited planning • Model-based recovery	Muli-spacecraft • Contingency planning • Active diagnostic testing
Modular & Scaleable Architecture	• Partial modular flight s/w architecture • 10% reuse s/w	• Modular flight s/w architecture • 30% reuse s/w	• Modular flight/grd s/w architecture • 70% reuse s/w
Navigation	Autonomous deep space optical navigation for cruise	Autonomous deep space formation navigation	Autonomous navigation for rendezvous & landing
Guidance & Control	Onboard attitude planning & control for autonomous SEP cruise & flyby	Two spacecraft formation keeping	Multi-platfrom onboard initialization & formation keeping
Onboard Science		Feature recognition & retargeting	Adaptive object recognition
Justified Operations	Beacon operations with limited data analysis & summary	Semi automated mission planning	PI controlled mission planning

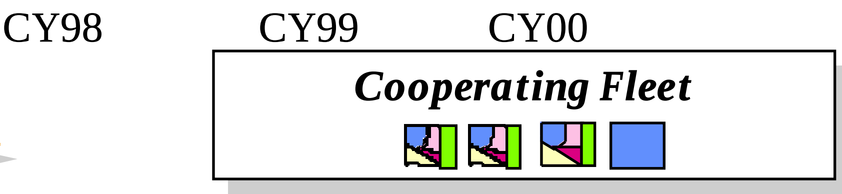
Self-Directing
Self-Protecting

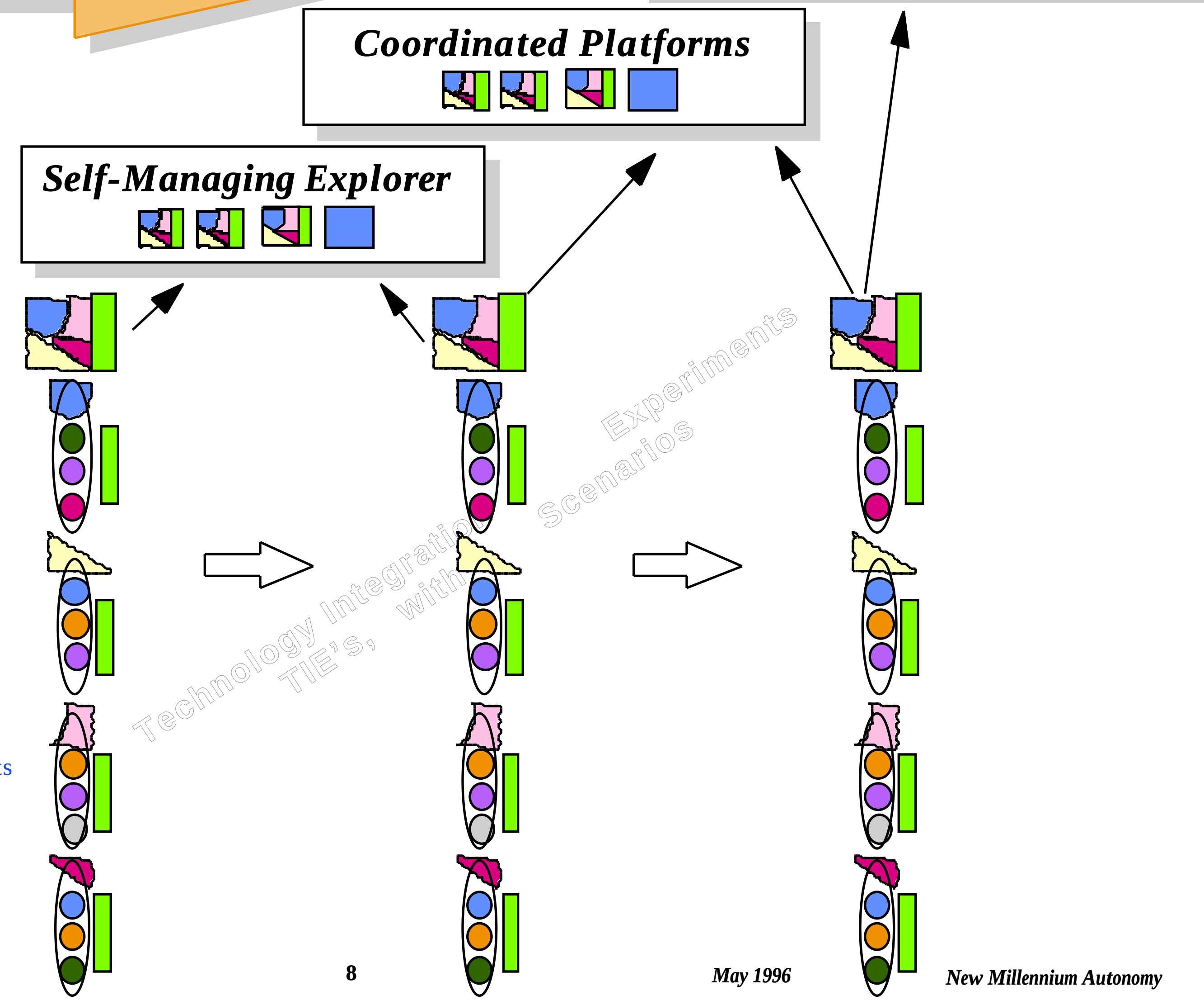
Self-Mobilizing

Self-Recognizing

PI-Directing

Autonomy Technology Development Through IFD's





Phased Integrated Feasibility Demos (IFDs)

Remote Agent -Autonomy Architecture & Functionality
- Executive
- Planning & Scheduling
- Fault Protection

Autonomous GN&C
- Navigation
- Control
- Sensors

Science & Mission Operations
- Engineering & Science Data Processing
- Beacon / Justified Ops
- "Virtual" Connection w / Scientists

Formation Flying
- Synchronization & time tagging
- Distributed Architecture
- Control within a cluster
- Control of whole cluster

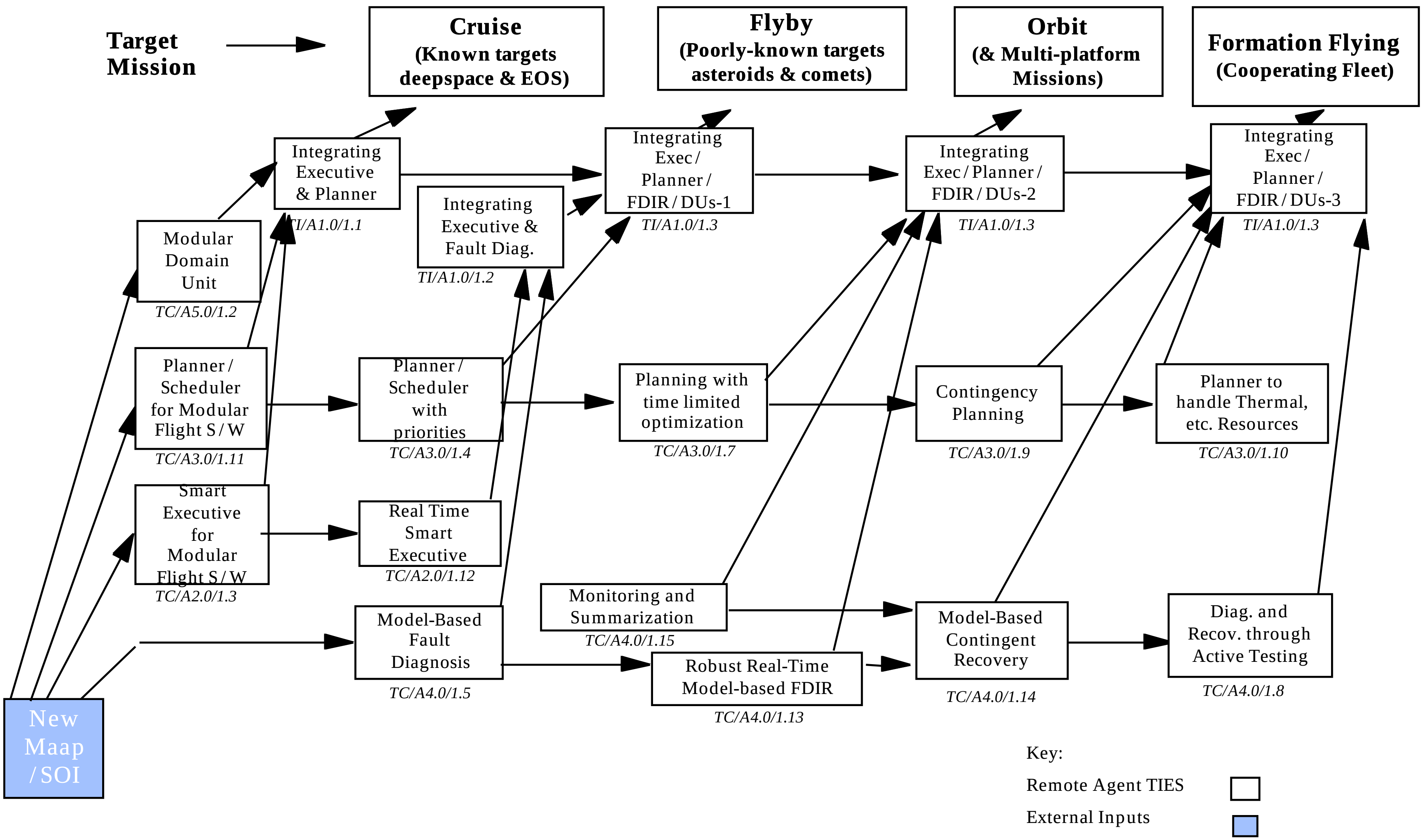
Remote Agent Technology Roadmap

Technology	Current Capability	CY1997	CY2000	Vision
Architecture	Flat system; Clear separation between ground ops and spacecraft functions; No software reuse	Hierarchical command structure; Standardized interfaces; 20% software reuse **(TC/A-DU/Mod, TC/I-Sys/EDP1)**	Transfer of functionality from ground ops to spacecraft; Reusable modules; 50% software reuse **(TC/I-Sys/EDP2, TC/I-Sys/EDP3)**	Multi-level *information* flow; Library of reusable components (mix & match); Run-time code migration
Executive	Linear sequences; Tightly scheduled; Inflexible Custom-built	Conditional sequences; Reactive to contingencies; Multi-tasking; **(TC/A-Exec/Mod, TC/A-Exec/RealTime, TC/I-Sys/E&D)**	Handle novel situations and unexpected contingencies; Detect resource conflicts **(TC/A-P&S/Conting)**	Integrate goal- and event-driven behaviors; Anticipate contingencies; Real-time scheduling and load-balancing
Tools	Manual design; Some (non-integrated) tool support	Code generation for interfaces between modules; Test generation and advanced simulation capabilities **(TC/S-Anlz/TestGen)**	Tools for design and verification of conditional sequences & FDIR **(TC/S-Design/FDIR, TC/S-Anlz/Plan, TC/S-Design/DU, TC/S-Anlz/Res)**	Automated synthesis of s/c systems from high-level specs and requirements
Planning/ Scheduling	PreLaunch: Humans - Contingency Mission: S/C- Execution, Humans - Replanning	PreLaunch: Automated - Sequential Mission: Automated nominal priority-based plans and some replanning (TC/A P&S/Pri)	PreLaunch: Automated - Conting. Mission: Replanning, Conditional planning, Contingency planning (**TC/A-P&S/Time,** TC/A P&S/Conting)	PreLaunch: Goal Definition Mission: S/C takes full charge of all resources
FDIR (Fault Detection, Isolation, and Recovery)	Rule-based on-board algorithms; time and persistence sensitive Recovery of capability managed primarily on ground by humans.	Modular, model-based FDIR onboard. Limited response to unanticipated, multiple faults. Some modular responses handcoded. (TC/A-FDIR/Mod, TI/A-Sys/E&D, TI/A-Sys/EDP1)	Active diagnostic testing and flexible contingent response; model-based configuration management; some statistical methods for FD. (TC/A-FDIR/Conting, TC/A-FDIR/Active, TC/S-Design/FDIR, TI/A-Sys/EDP2&3)	High-level, model-based programming of hybrid discrete-continuous reactive system. Behavior distributed across constellation.

Remote Agent: Benefits to Space Community

	CY97	CY00
Scientist/Users	Interact at high level of abstraction; Reduced down time demonstrates potential for increased science return.	More Reliable goal achievement. Minimal down time and low cost enable new paradigm for exploration
Mission Operators	Reduced operation staff Flexible ground-s/c interaction Reduced monitoring requirements	More reliable systems; Less dependence on ground intervention Auto recovery and active diagnosis enables Tiger team to manage spacecraft fleet.
S/C Developers	Reusable architecture. High level specification language Model-based programming enables quick FDIR prototyping.	Easy to express design decisions Model-reuse and programming enable fast assembly of reliable spacecraft.
Technologists	New insights into building autonomous systems and key research issues.	New paradigm for research, on autonomous hybrid systems.
Commercial Sector	Transfer technology to other real-time autonomous systems such as robotics and process control New methodology for building commercial S/C initiated.	Benefits to computer-aided software engineering Model-based programming broadly applied to build, robust autonomous systems.

Remote Agent Build-up Plan



Remote Agent
TC/A-FDIR/Rob (Component)
TC/A4.0/1.13

Title: Robust Model-Based Isolation and Recovery in Real-time

Technical Focus:

To have broad coverage, recovery must be able to flexibly construct sequences of recovery actions and fault isolation must be able to identify failures that manifest themselves over a period of time. To be responsive, both capabilities will provide any-time algorithms that are guaranteed to provide a safe solution at any point in time, with the quality of solution improving over time.

Demonstration:

Using a spacecraft simulator, Isolation correctly identifies failure modes whose symptoms manifest themselves over a period of time. Recovery correctly responds to failures involving the interleaving of sequences of actions, and responds to failures where the source and cause is ambiguous. Isolation and recovery actions requested after successive times lead to improved quality.

Evaluation Metrics:

Response time

Percentage of correct responses by fault class

Percentage of time that the system enters safing mode.

Assumptions:

Spacecraft models, MMI

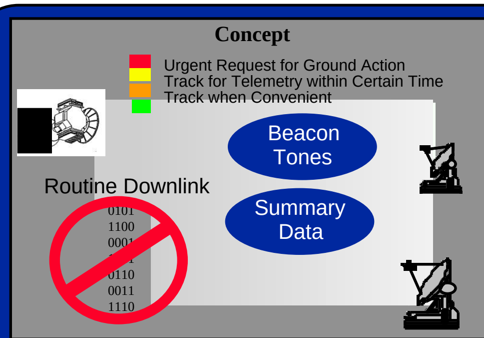
Inputs: NONE

Outputs: TI/A-Sys/EDP2 *(TI/A1.0/1.3)*

Who: AMES/JPL/TRW **When: FY97** **Cost: $450K**

Autonomy Technology Flight Experiments

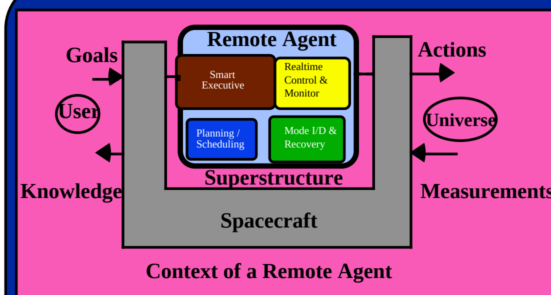
NMP DS-1



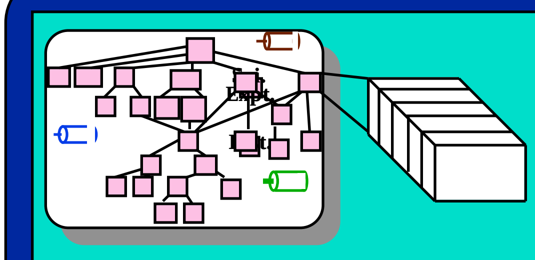
Beacon Operations

Self-Directing
Self-Protecting

NMP DS-1

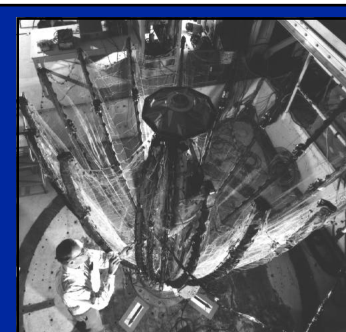


Goal-Directed Planning/ Scheduling &Smart Executive



Flight & Ground Systems Architecture

NMP DS-1



Health Monitoring & Fault Protection

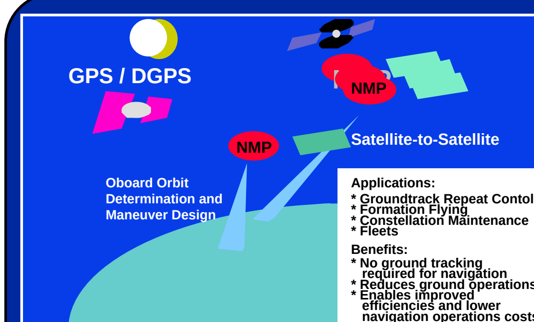
Self-Mobilizing

NMP DS-1

Autonomous Guidance, Navigation & Control

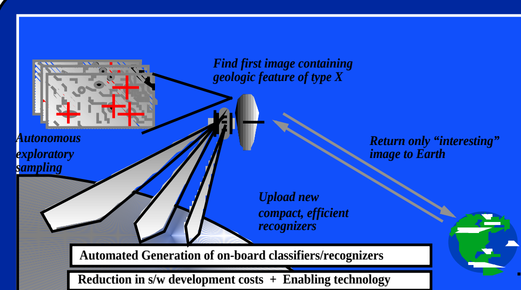
NMP DS-1

NMP EO-1 ?



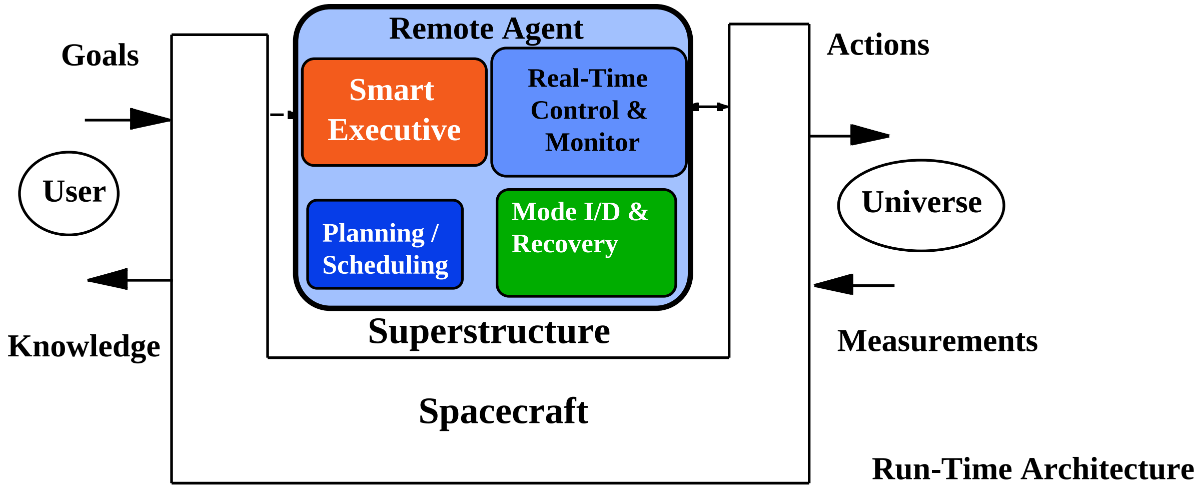
Auto-Navigation for Formation Flying

NMP DS-1 ?



Science Data Processing

Autonomy Remote Agent - Run-Time Architecture



Context of a Remote Agent

• Planning & Scheduling

Constraint-based planning & scheduling, to ensure achievement of long-term mission objectives and manage allocation of system resources (e.g. time, orders, power, fuel)

• Smart Executive

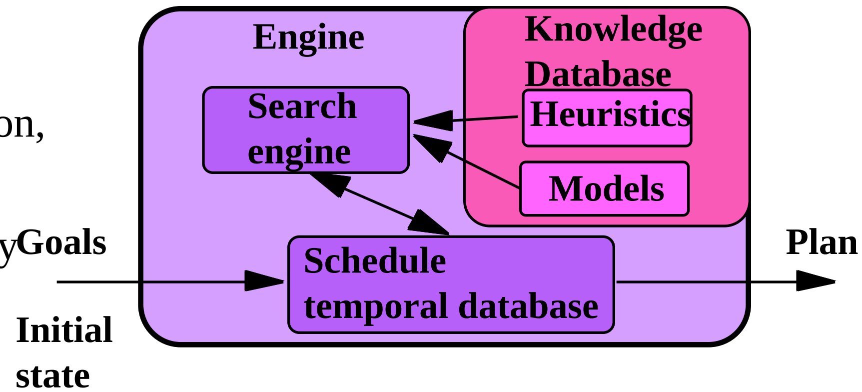
Robust, multithreaded execution, to reliably execute planned sequences under conditions of uncertainty, to rapidly respond to unexpected events such as component failures, and to manage concurrent real-time activities

• Mode Identification & Recovery

Model-based diagnosis, to confirm successful plan execution and to infer the health of all system components based on inherently limited sensor information

Remote Agent Key Idea: Design Operational Behavior into the Spacecraft Before Launch

- Spacecraft carries explicit models of the operational behaviors, e.g.,
  - **Resource constraints**: power, pointing direction, science/nav camera
  - **Hardware constraints**: warm-up times, battery charging cycles, task precedence relations
  - **Nominal & Failure modes**: all hardware (e.g., bus, computer, telecon system), system modes



- Reasoning engines look for conflict free procedures to operate spacecraft in real-time

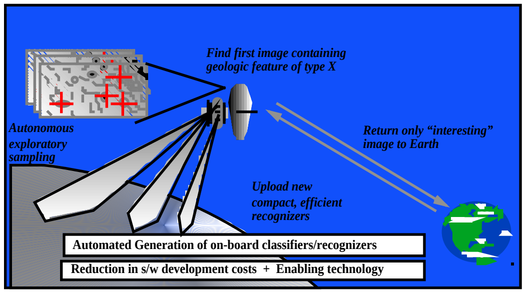
Benefits: Reduces operations requirements & endows spacecraft with multiple means to function.

Key Idea: Transform the Spacecraft from an Open Loop System to a Closed-Loop System

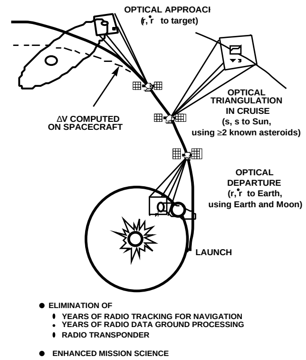
- At the level of servo systems, current spacecraft provide feedback-based control loops, e.g. attitude control.
- However, at the level of **goals** (commands to the spacecraft), current spacecraft is open-loop; the feedback loop for goals is a labor-intensive and slow ground-based process.
- Model-based autonomy system closes the loop on-board at the goal level.

Benefits: Allow us
to go into environment that is more uncertain &
to achieve our goal more reliably in the face of problems.

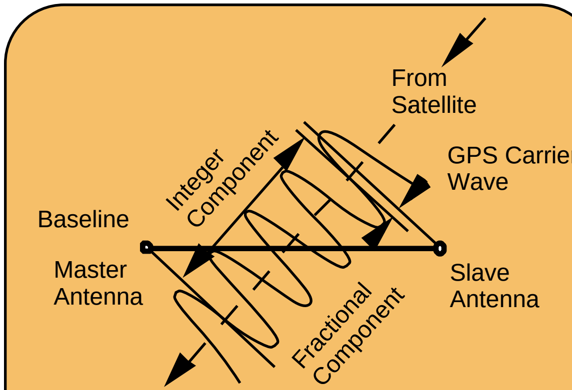
Teaming



Science Data Processing
- **South West Research**
- **NASA**

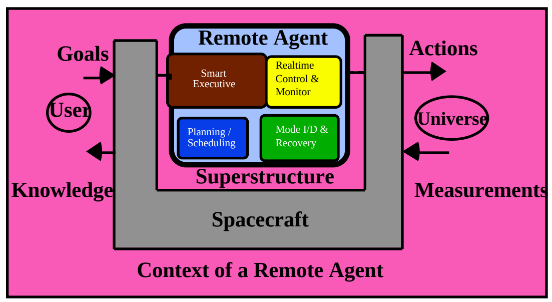


Optical Navigation
- **NASA**



Differential Carrier Phase GPS showing the relationship between the master and slave antenna

Precision GPS
- **Stanford University**

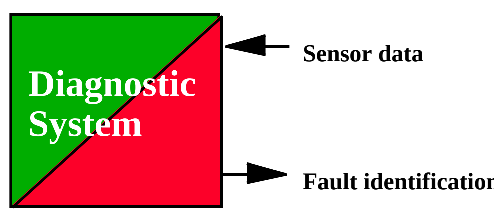


Autonomy Superstructure
- **NASA**

Task- Level Control | **Real-Time Control**

Planning, Scheduling, Reasoning — **Sequencing, Monitoring, Error Recovery** — **Servoing, Feedback**

High Level Design Tool & Language
- **Carnegie Mellon University**



Fault Detection & Isolation
- **TRW**

Science &Mission Operations & Processes - Beacon mode
- **ISX**
- **Stanford University**

Look Ahead - Technology Gaps

- **Rendezvous & Landing**
- **Formation Flying & Multiple Spacecraft Systems**
- **Payload Data Processing**
- **Testing**